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Citation for published version:

Vaughan, DG, Barnes, DKA, Fretwell, PT & Bingham, RG 2011, 'Potential seaways across West Antarctica', *Geochemistry, Geophysics, Geosystems*, vol. 12, no. 10, Q10004, pp. 1-11.
<https://doi.org/10.1029/2011GC003688>

Digital Object Identifier (DOI):

[10.1029/2011GC003688](https://doi.org/10.1029/2011GC003688)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Publisher's PDF, also known as Version of record

Published In:

Geochemistry, Geophysics, Geosystems

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Potential seaways across West Antarctica

David G. Vaughan, David K. A. Barnes, and Peter T. Fretwell

British Antarctic Survey, Natural Environment Research Council, Madingley Road, Cambridge CB3 0ET, United Kingdom (d.vaughan@bas.ac.uk)

Robert G. Bingham

School of Geosciences, University of Aberdeen, Elphinstone Road, Aberdeen AB24 3UF, United Kingdom

[1] The West Antarctic ice sheet (WAIS) has long been considered vulnerable to rapid retreat and today parts are rapidly losing ice. Projection of future change in WAIS is, however, hampered by our poor understanding of past changes, especially during interglacial periods that could be analogs for the future, but which undoubtedly provide an opportunity for testing predictive models. We consider how ice-loss would open seaways across WAIS; these would likely alter Southern Ocean circulation and climate, and would broadly define the de-glacial state, but they may also have left evidence of their existence in the coastal seas they once connected. We show the most likely routes for such seaways, and that a direct seaway between Weddell and Ross seas, which did not pass through the Amundsen Sea sector, is unlikely. Continued ice-loss at present rates would open seaways between Amundsen and Weddell seas (A-W), and Amundsen and Bellingshausen seas (A-B), in around one thousand years. This timescale indicates potential future vulnerability, but also suggests seaways may have opened in recent interglacial periods. We attempt to test this hypothesis using contemporary bryozoan species assemblages around Antarctica, concluding that anomalously high similarity in assemblages in the Weddell and Amundsen seas supports recent migration through A-W. Other authors have suggested opening of seaways last occurred during Marine Isotope Stage 7a (209 ka BP), but we conclude that opening could have occurred in MIS 5e (100 ka BP) when Antarctica was warmer than present and likely contributed to global sea levels higher than today.

Components: 5700 words, 5 figures, 3 tables.

Keywords: climate change; ice sheets; oceans.

Index Terms: 0410 Biogeosciences: Biodiversity; 0416 Biogeosciences: Biogeophysics; 0726 Cryosphere: Ice sheets.

Received 5 May 2011; **Revised** 11 August 2011; **Accepted** 22 August 2011; **Published** 7 October 2011.

Vaughan, D. G., D. K. A. Barnes, P. T. Fretwell, and R. G. Bingham (2011), Potential seaways across West Antarctica, *Geochem. Geophys. Geosyst.*, 12, Q10004, doi:10.1029/2011GC003688.

1. Introduction

[2] The West Antarctic ice sheet (WAIS) has long been considered capable of rapid collapse [Katz and Worster, 2010; Mercer, 1978; Schoof, 2007; Thomas et al., 1979; Weertman, 1974], causing global sea level rise of 5 m [Lythe et al., 2001]. Recent ice-loss from the Amundsen Sea embay-

ment [Pritchard et al., 2009; Rignot et al., 2008; Wingham et al., 2006] has amplified this concern, albeit with a reduced sea level rise [Bamber et al., 2009b]. Projections of the risk associated with ice sheet collapse will eventually emerge from physically based models of ice-dynamics driven by external atmospheric and ocean forcing, but demonstrating that such models have sufficient skill to

be reliable is currently difficult. This difficulty could be reduced with an improved understanding of how ice sheets changed during recent interglacial periods, some warmer than today, which might serve as analogs for the future, and which undoubtedly provide an opportunity to test ice-dynamics models with (albeit incomplete) observational data. However, while most researchers have agreed for many years that WAIS most likely waxed and waned substantially throughout late Quaternary glacial cycles [e.g., *Mercer*, 1978] there are almost no direct observations that constrain its size at any time prior to the Last Glacial Maximum (~18 ka BP).

[3] Here we consider a particular feature of WAIS deglaciation that has rarely been discussed; these are the seaways that could open across the deep basins currently occupied by ice, allowing the transfer of water, heat and biological material between Antarctic coastal seas. The existence of such seaways would usefully define the minimum contribution of WAIS to sea level rise, and may have significantly altered Antarctic climate and Southern Ocean circulation. Here we derive the most likely routes for seaways, and their vulnerability to current rates of ice loss, and we consider whether the biology of Antarctic coastal seas contains evidence that they were open in recent interglacial periods.

2. Topographic Analysis

[4] Progressive thinning of coastal ice resting on a bed below sea level will eventually allow it to float. If such thinning connected two coastal seas, whether or not a floating ice shelf remained, seawater would pass freely beneath the ice and between the seas, forming an open seaway. Although the impact of such seaways on the oceanography of the Southern Ocean and Antarctic climate is likely to have been substantial, to date there has been little effort to investigate their importance. The only comparable seaway in existence today, that beneath George VI Ice Shelf on the Antarctic Peninsula, has a strong ocean current flowing through it, which influences considerably oceanography of the nearby continental shelf [*Jenkins and Jacobs*, 2008].

[5] We used a digital elevation model (DEM) of the sub-glacial bed in Antarctica to map the thickness of ice that would have to be lost before the onset of flotation (Figure 1). In most areas, our DEM was a recently improved sub-glacial topography [*Le Brocq et al.*, 2010] compiled from many sources and including much recent airborne survey

data from WAIS [*Holt et al.*, 2006; *Vaughan et al.*, 2006]. To this, were added new radar data we collected in 2009/10 in the area inland of Eltanin Bay (Figure 1). These data showed a deep but narrow (~10 km) trough beneath this portion of the ice sheet that was important to understanding the most likely route for a seaway between the Bellingshausen and Weddell seas.

[6] Our assessment of the ice-thickness above flotation (Figure 1) used contemporary sea level, because we are interested primarily in geological periods (interglacials) during which sea levels and global ice volume were comparable to present. Periods of substantially lower sea level that would decrease the potential for seaways in Figure 1, would likely occur at times when the Antarctic ice sheet was more not less extensive. Finally, our assessment of the ice-thickness above flotation (Figure 1) differs from the map of “ice-thickness above buoyancy” presented by *Le Brocq et al.* [2010]. Except inland of Eltanin Bay, that assessment used similar data to our own, but in areas where the bed is currently above sea level, *Le Brocq et al.* showed the ice-thickness above buoyancy as the local ice thickness, rather than masking these areas out entirely as we have done, to indicate that open water in these areas is not possible.

[7] In West Antarctica, there appear to be several candidate seaways that would connect coastal seas if sufficient ice were lost. We identified the most likely routes for these seaways as those that would require the removal of least ice for flotation to begin; for brevity we name these potential seaways A-B, A-R, A-W, B-W, and R-W, denoting their connections to the Amundsen, Bellingshausen, Ross and Weddell seas. This criterion for choosing the most likely seaways naturally identifies routes that tend to lie in the deepest troughs, currently occupied by some of the most significant glaciers in WAIS, which makes sense on two other grounds. First, the capacity of ocean water to melt ice increases with depth [*Millero*, 1978] so that the capacity of warm water incursions to effect ice melt is strongest at deep grounding lines. Second, the effect of coastal ice thinning in both Antarctica and Greenland appears to be transmitted inland by ice-dynamic effects that are strongest along fast-flowing glaciers [*Pritchard and Vaughan*, 2007].

[8] Figure 2 shows cross-sections along these potential seaways including the present and isostatically adjusted (Airy compensation) sub-glacial topography. Examination of these cross-sections

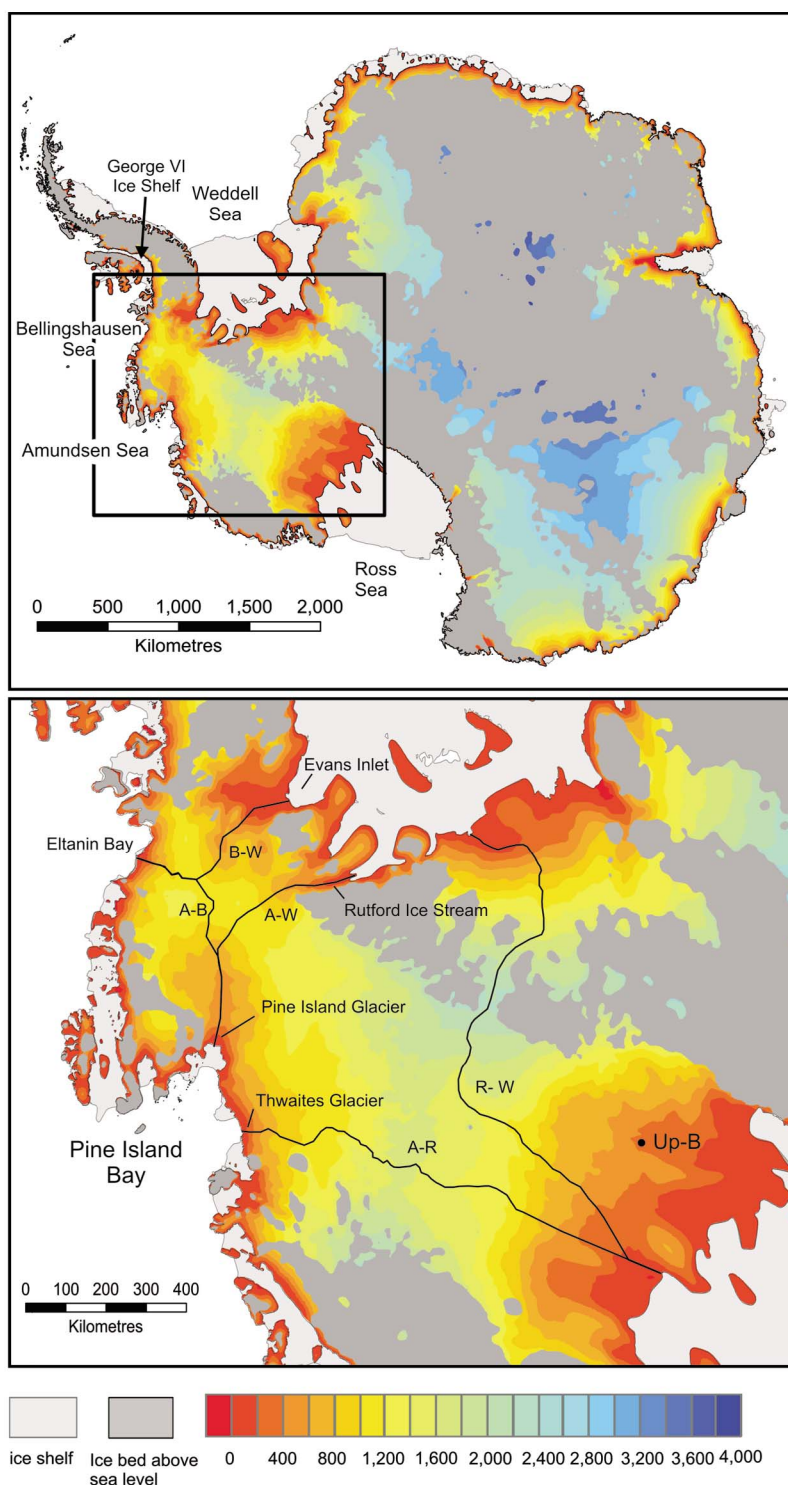


Figure 1. Map of Antarctica (with inset of West Antarctica) showing the thickness of ice that would need to be removed before flotation would occur, calculated assuming an ice-density of 910 kg m^{-3} , seawater-density of 1030 kg m^{-3} , a satellite-derived ice-surface elevation model [Bamber *et al.*, 2009a] and sub-glacial bed elevation [Le Brocq *et al.*, 2010] supplemented with unpublished data collected inland of Eltanin Bay in 2009/10. Elevations referenced to the EIGEN-GL04c geoid and current sea level. The labeled sections, defining our hypothesized seaways, were chosen as the routes requiring least ice loss. The location of Up-B is shown according to the position given by Whillans *et al.* [1987].

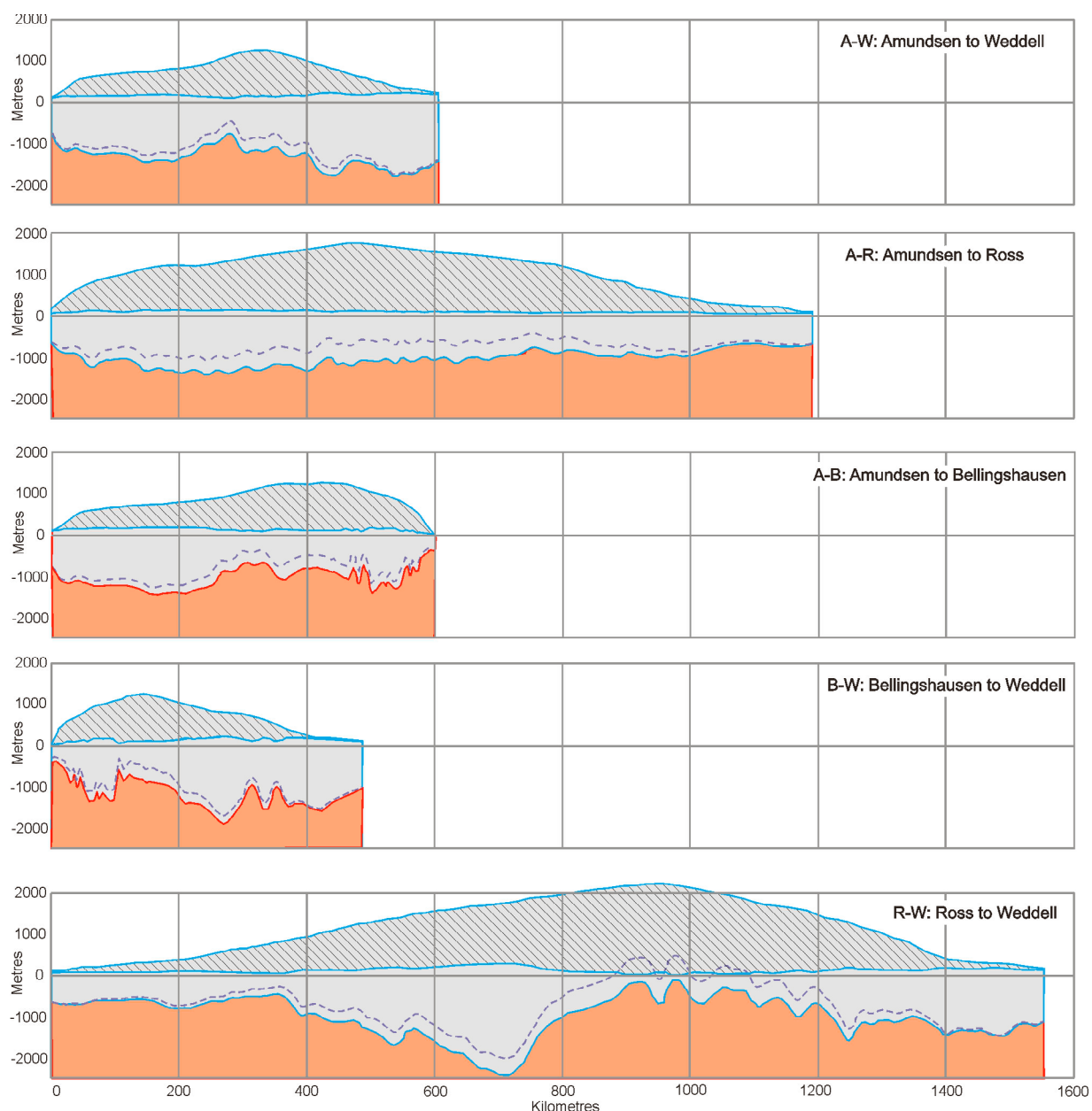


Figure 2. Vertically exaggerated cross-sections along candidate seaways shown in Figure 1. The elevation of the current ice surface and bed, and flotation level calculated assuming ice density of 910 kg m^{-3} and seawater density of 1030 kg m^{-3} are shown. The portion of ice that would need to be removed for flotation to occur is indicated by hatching. The bed elevation achieved after full Airy isostatic adjustment is indicated by the dashed line, assuming upper-mantle density of the 3320 kg m^{-3} [see *Ranalli*, 1995, p. 132].

shows that a direct Ross Sea to Weddell Sea (R-W) seaway is extremely unlikely. While the density of measurements in this area is lower than other key areas in West Antarctica, the coverage is sufficient to show that there are no significant sub-glacial troughs that could provide a significant seaway through this part of the ice sheet. Using the present gridded topography, we find that at the shallowest point along this section it would require loss of a

great thickness of ice ($>2000 \text{ m}$) before flotation. Since it should be expected that around one third of the total isostatic uplift shown in Figure 2 would result from the instantaneous elastic response of the crust and lithosphere [e.g., *Watts*, 2001, pp. 227 and 240], the uplift resulting from 2000 m of ice overburden would mean that even under conditions of rapid ice loss, this section is unlikely to open as a significant seaway.

Table 1. Sensitivity of Candidate Seaways to Ice Thinning^a

		Volume of Ice Above Flotation Along Section (km ³ per km of section width)	Rate of Ice Loss From Section (km ³ a ⁻¹ per km of section width)	Indicative Timescale for Initiation of Seaway (years)
Amundsen-Weddell	A-W	410	0.33	1200
Amundsen-Ross	A-R	1200	0.30	4030
Amundsen-Bellinghshausen	A-B	436	0.48	910
Bellinghshausen-Weddell	B-W	273	0.15	1830
Ross-Weddell	R-W	1700	0.02	85000

^aThe volume of ice above flotation was calculated directly from sections shown in Figure 2, and the rate of current ice loss was derived from using ICESat data (2002–2007) [Pritchard *et al.*, 2009] to determine the current rate of ice-loss along the section, but ignoring areas of ice-thickening assumed to have occurred as a result of short-term variability in snowfall. The indicative timescale for the initiation of each seaway was calculated as the simple division of the first two quantities.

[9] In contrast, the remaining four seaways (A-W, A-R, A-B and B-W) are strong candidates. Three of these (A-R, A-B, A-W) would provide deep and wide (>30 km) seaways across WAIS, while the other (B-W) follows a comparatively narrow (~10 km) channel in the bed.

[10] Recent ice-surface elevation change across WAIS has been mapped using several techniques [e.g., Pritchard *et al.*, 2009; Rignot *et al.*, 2008; Wingham *et al.*, 2006]. While there has been some ice-thickening resulting from precipitation changes [Wingham *et al.*, 2006] and the historic deceleration of Kamb Ice Stream (formerly Ice Stream C) [Joughin and Tulaczyk, 2002], the pattern during the last two decades has been dominated by accelerating ice-loss from the coastal margin of the Amundsen Sea embayment. Although not intended as a prediction, we calculated how long current rates of ice-loss [Pritchard *et al.*, 2009] along each section would need to persist before the seaway opened (Table 1). Since areas of ice-thickening appear to be transient, we did not include their negative contribution. Most significantly, at current rates, it would take around a thousand years to open A-B and A-W. These timescales are significant because in rather broad terms they indicate the severity of current changes and relative vulnerability to future change, but more significantly because they lead us to the expectation that these seaways could well have opened in one or more recent interglacial periods. Although Eemian ice has yet to be recovered from West Antarctica, evidence from other Antarctic ice cores shows that the last interglacial (MIS 5e) was warmer than present for 10 ka, and was substantially warmer (>6K) for 2.5 ka [Sime *et al.*, 2009]. Given the strong coupling expected between atmospheric and ocean circulation around WAIS [Meredith and King, 2005; Thoma *et al.*, 2008], it is unlikely that WAIS survived such a period of relative

warmth without these seaways opening: an interpretation supported by recent evidence that during MIS 5e ice-loss from Antarctica contributed to substantially higher global sea levels [Kopp *et al.*, 2009].

[11] Testing this assertion is currently difficult because of the lack of data available to constrain the extent of WAIS prior to the LGM. The most sophisticated model-based ice sheet reconstruction available [Pollard and DeConto, 2009] showed roughly the same seaways as we identified, but suggested that they all opened, and closed for the last time, during MIS 7a (~209 ka). In that reconstruction, none opened during MIS 5e. However, the authors of that reconstruction noted that their forcing parameterizations, based on far-field oceanic temperatures, probably led to imprecise timing of late-Pleistocene WAIS-collapses. The widely cited interpretation of sub-glacial sediments from Up-B (Figure 1) is similarly problematic. Those sediments indicated exposure to marine conditions during an unidentified Pleistocene interglacial [Scherer *et al.*, 1998], but our topographic analysis indicates that Up-B is ~200 km distant from the most likely route for seaway A-R, and is irrelevant to the most vulnerable seaways (A-W, A-B; Figure 1). Similarly, the record obtained from the ANDRILL marine-sediment core, acquired from a site currently beneath East Antarctic ice draining through the Ross Ice Shelf [Naish *et al.*, 2009], although it has some implications for WAIS, does not constrain the late-Pleistocene condition of the Amundsen Sea embayment. Finally, analysis of contemporary biodiversity of cheilostome bryozoans around Antarctica has been used to suggest a late Quaternary seaway connecting the Weddell and Ross seas [Barnes and Hillenbrand, 2010]; whereas we have shown that the direct seaway R-W is unlikely. This final approach is, however, potentially very valuable, and we have revisited it

with the benefit of the first samples of bryozoans assemblages from the Amundsen Sea now available to us.

3. Biodiversity Analysis

[12] Bryozoans provide a valuable tool for investigating historical environmental change [McKinney *et al.*, 1998]. Almost all adult colonies are sessile, meaning they are fixed to their substrate, but their young occur as free-living benthic larvae and although these sink in the water column, this allows species some limited capacity for dispersal [Barnes and Griffiths, 2008; McKinney *et al.*, 1998]. A handful of bryozoan species have pelagic larvae and some encrust algae which might be rafted during storms, but for the vast majority of species we estimate dispersal potential of tens of meters per generation at depths typical of the continental shelf, to hundreds of meters in shallower environments. Except at small scales (which may be dominated by habitat differences) there is a general expectation that similarity between biological assemblages which have limited dispersal such as bryozoans, decreases with distance apart.

[13] Many bryozoan species are robust: they thrive in Antarctic intertidal zones, in ice-scoured shallows and under ice shelves. Recent analyses [Barnes and Kuklinski, 2010] have suggested that despite experiencing reduced salinity, mechanical disturbance, high sedimentation and low food availability, they survived the LGM in refugia around Antarctica and subsequently recolonised the continental shelves. These factors are reflected in species distribution: ~500 (57%) species are endemic to Antarctica with many restricted to particular regions. Thus, even on contiguous continental shelves, bryozoans show considerable variation while preserving a strong geographic affinity [Jackson and Cheetham, 1991].

[14] We have analyzed published cheilostome bryozoan distribution data [Barnes and Hillenbrand, 2010] from 12 sites around Antarctica compiled from published sources (summarized by Barnes and Hillenbrand [2010] and Barnes and Kuklinski [2010]). These data were supplemented by data from samples at depths of 500–1500 m on the Amundsen Sea continental shelf acquired during the BIOPEARL II scientific cruise of 2008. In summary, the data from each site reflect the known bryozoan species across all shelf depths (to maximum depths of ~1000 m max), and a variety of overlying ice conditions, substrata and water properties.

[15] Several species (e.g., *Osthimosia rudicula* and *Pyripoides uniserialis*) have been found to date exclusively on the Weddell, Amundsen and Bellingshausen sea continental shelves. Several more species have been found only in the Ross, Weddell, Amundsen, and Bellingshausen sea continental shelves. These include species such as *Amphiblestrum rossi*, *Aspericreta favulosa*, *Buffonellaria frigid*, *Cellarinella margaritae*, and rarities such as *Dakariella dabrowni*. This is not always evident from open access sources such as international databases, even those checked by expert taxonomists. This is because species without precise geo-referencing cannot be included (e.g., *A. favulosa*, *B. frigida* or *D. dabrowni* all known in the Ross Sea; see Hayward [1995], but not for exact latitude and longitude) and due to sections of the literature remaining to be added (e.g., *B. frigida*, *D. dabrowni* and *P. uniserialis* known in the Weddell Sea from Russian literature [see Gontar and Zabala, 2000]). Furthermore, existing records need to be constantly reconsidered in the light of reexamination; records for the South Orkney Islands of *A. favulosa* and for the north Antarctic Peninsula of *C. margaritae* [Barnes *et al.*, 2009] have now been recognized to be closely related congeners (*A. crassatina* and *C. watersi*). A report of *B. frigida* from the South Orkney Islands is now considered as a new congener species.

[16] Analysis of our database shows three species have been found exclusively in the Weddell, Amundsen and Bellingshausen seas; while 11 other species have been found exclusively in the Ross, Weddell, Amundsen, and Bellingshausen seas. Around all Antarctica, the number and proportion of shared species was generally highest between adjacent regions, but with two notable exceptions. The similarity of the Amundsen Sea samples to the Ross and Weddell seas samples was 70% higher than to other areas (mean 20.1% \pm SE 1.2). The Amundsen Sea shared more species with the Weddell Sea than anywhere else (93 or >82%), and likewise the Ross Sea shared most with the Weddell Sea (142 or >74%). In contrast, the Amundsen Sea shared relatively few species with similar nearby localities (e.g., Bellingshausen Sea, 53.3%), indicating that similarity of Amundsen Sea, and Weddell and Ross sea faunas cannot be explained by ecological similarity and distance alone. These features of the bryozoan distribution may be sufficient to suggest that open seaways once allowed better transport to and from the Amundsen Sea population than would be expected via the current sea

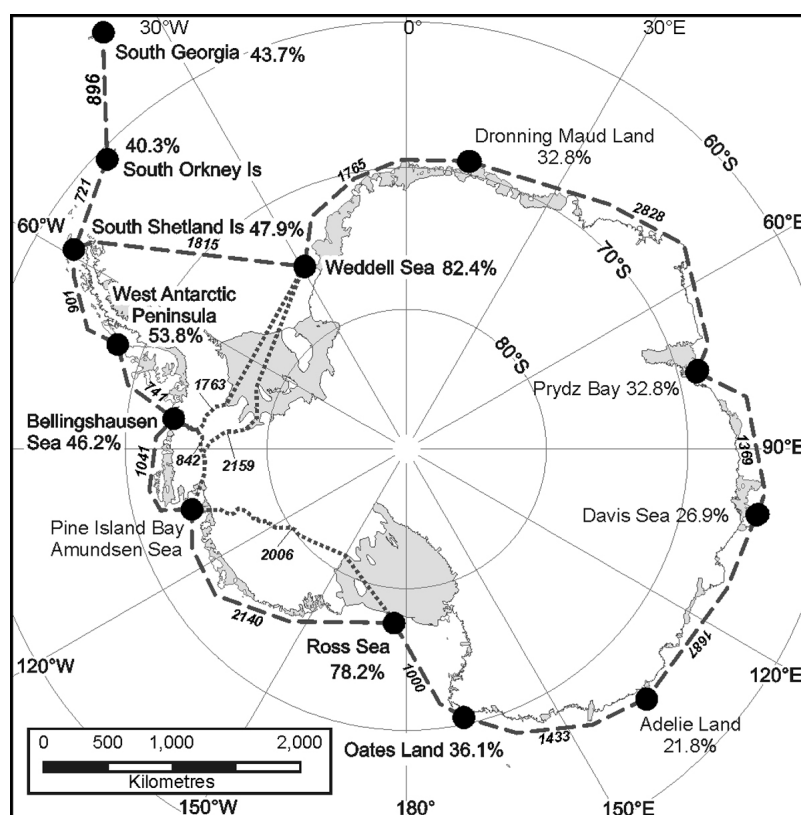


Figure 3. Centres of Bryozoan sample locations, with distances (dashed and dotted lines) between sample locations used in calculations. Also shown are the percentage similarity of assemblages with the assemblage in Pine Island Bay (Amundsen Sea). Dotted lines show distances along hypothesized seaways.

routes but, to formalize this analysis, we have also undertaken a statistical analysis.

[17] We calculated Sørensen's Similarity Index [Sørensen, 1948] for pairs of assemblages and investigated its correlation with the sea-distance between the sampling points, calculated using both the current ice sheet configuration and with the candidate seaways open (Figure 3). We used Sørensen's Similarity Index (Q_s) in the form

$$Q_s = \frac{2N_{12}}{N_1 + N_2}$$

where N_1 and N_2 are the number of species in each of the samples, and N_{12} is the number of species that exist in both samples.

[18] Because the opening of A-B does not substantially alter the distances between sampling sites, that seaway is not included in the following discussion. Considering all Antarctic samples (78 pairs, Table 2 and Figure 4), and with the ice sheet in its present configuration, there is a correlation between the distance between sites and the

similarity of the bryozoan species found around those sites ($r^2 = 0.307$), which is in line with our expectation concerning the dispersal of species. The correlation is, however, much lower if we consider only sample-pairs that include at least one site in West Antarctica (33 pairs, $r^2 = 0.13$, Table 3 and Figure 5a). In this case, the similarity of sites in the Weddell, Amundsen and Ross seas is apparently anomalously high given their separation. However, overall the correlations rise back close to the pan-Antarctic values if we use distances calculated with individual seaways open (Table 3 and Figure 5b). In this case, the similarity between Ross and Weddell sea is still higher than expected, but the Amundsen-Weddell and Amundsen-Ross pairs are close to the value suggested by their separation. The highest correlation was achieved with all seaways open, but this is not significantly higher than with A-W alone, or combinations that include A-W. In all our analyses the statistical measures showed that an A-W seaway explained similarity patterns considerably better than no seaways or any other single seaway, and only multiple seaways involving A-W marginally increased fit.

Table 2. Results of ANOVA Regression of Sørensen's Similarity Index of Species Observed in Geographic Samples, Against Distance Between Sampling Sites Calculated on the Basis of Different WAIS Seaways Being Open: Analysis for All Pairings of Sites Around Antarctica, Including Pairs That Do Not Include a West Antarctic Site^a

	Seaways Closed	A-W	B-W	A-R	A-W B-W	B-W A-R	A-W A-R	A-W B-W A-R	A-W A-R Corr.
r^2	0.307 (Figure 4)	0.367	0.341	0.302	0.364	0.350	0.372	0.369	0.396
F	35.2	45.7	40.9	34.3	45	42.5	46.5	45.9	51.4
p	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

^aThe addition of A-B makes only marginal (non-significant) differences to the correlations and so is not included. A further addition is "A-W A-R Corr." which was based on an enhanced calculation of the migration distance, where distances over water deeper than continental shelf depths was doubled (to reflect the likely much greater difficulty of travel) and the distance between shelves through new seaways halved (to reflect the likely strong currents and thus increased opportunities for dispersal).

[19] Given this line of reasoning, it is perhaps surprising that the highest similarity index occurs for the Ross-Weddell samples (Figures 4 and 5), however, this may be due to the quantity of data available. The Amundsen Sea population was determined from 40 individual samples collected during a single scientific cruise, compared with more than a century of sampling in the Weddell and Ross seas. Although Sørensen's Similarity Index does take some account of the sample size, an increase in the size of the Amundsen Sea sample would perhaps show more shared species and increase the Amundsen-Weddell and Amundsen-Ross similarity indices. Nevertheless, the fact that, without seaways, the pairs representing A-W and R-W are so much higher than expected, and that overall our correlations that include West Antarctic sites appear to be so similar to the pan-Antarctic correlation when the seaways are open, does appear to support the hypothesis of opening of A-W, and perhaps also of opening of A-R and B-W.

[20] The analysis would benefit substantially from a more highly differentiated database of bryozoan

species (more sites, and more samples) and by the inclusion of specific data that could be acquired from key sites around Antarctica (e.g., on the present continental shelf between the Amundsen and Ross seas). However, given these limitations, the simplest explanation of similarity data (in Tables 2 and 3 and Figures 4 and 5) is that a seaway recently linked and allowed transport of bryozoans between the Amundsen and Weddell Seas.

[21] While the foregoing discussion provides evidence only for the existence of open seaways, assigning a date to such events is much more difficult. We are cautious not to overstate the case, but our analysis of bryozoan biodiversity does suggest that the last closure of seaways probably took place relatively recently. It is expected that each post-glacial re-colonization of the continental shelves by bryozoans will dilute the signal of connectivity. So, the fact that the similarity of Amundsen and Weddell sea populations is as high as those between neighboring populations that are unlikely to have been separated by ice during MIS 5e (e.g.,

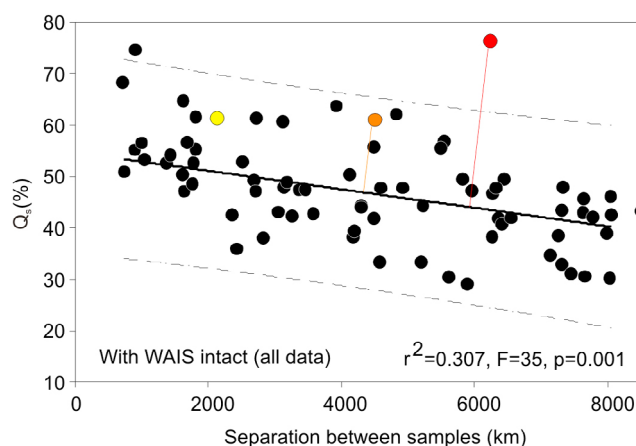


Figure 4. Sørensen's Similarity index (Q_s) of bryozoan species in all pairs of sites around Antarctica as a function of the current sea distance between the centers of those sites (see Figure 3). Specific pairs are highlighted by colored fill: red, Ross and Weddell seas (R-W); orange, Amundsen and Weddell seas (A-W); yellow, Amundsen and Ross seas (A-R). Dashed lines are 95% confidence interval.

Table 3. Results of ANOVA Regression of Sørensen's Similarity Index of Species Observed in Geographic Samples, Against Distance Between Sampling Sites Calculated on the Basis of Different WAIS Seaways Being Open: Analyses for Pairings That Include at Least One West Antarctic Sample

	Seaways Closed	A-W	B-W	A-R	B-W A-W	B-W A-R	A-W A-R	B-W A-W A-R	A-W A-R Corr.
r^2	0.134 (Figure 5a)	0.289	0.240	0.117	0.287	0.239	0.286	0.293 (Figure 5b)	0.348
F	5.95	14.0	11.1	5.2	13.9	11.1	13.8	14.3	18.9
p	0.02	0.001	0.002	0.029	0.001	0.003	0.001	0.001	0.001

South Shetland Islands and Antarctic Peninsula) can be explained if A-W was open in a recent interglacial – most simply, if it was open during MIS 5e.

4. Discussion

[22] In summary, our topographic analysis clearly identifies four candidate seaways across WAIS, none of which connect the Weddell and Ross seas without passing through the Amundsen Sea embayment ice sheet. This establishes the Amundsen Sea embayment ice sheet, not only as the center of current Antarctic ice loss, but one of key importance in understanding deglaciation during recent interglacial periods. The current pattern and rate of ice loss along the routes of the most likely seaways suggests A-W and A-B are the most vulnerable to the current pattern of change, but any or all could have been open during recent interglacial periods. Our analysis of Bryozoan biodiversity confirms that the Amundsen Sea was most likely the center of past seaways, with good evidence for the opening of A-W, and weaker evidence for opening of A-R and B-W.

[23] The methods currently at our disposal do not allow us to constrain, with confidence, which recent interglacial saw the last open West Antarctic seaways. However, given that during the last interglacial (MIS 5e), air temperature in Antarctica was substantially warmer than present for several thousand years [Sime *et al.*, 2009] and at the same time, ice-loss from Antarctica almost certainly contributed to higher global sea levels [Kopp *et al.*, 2009], it would appear that MIS 5e is a strong candidate.

[24] With ice sheets the largest source of uncertainty in projections of sea level [Intergovernmental Panel on Climate Change, 2007], there is an urgent need to demonstrate skill in ice sheet predictive modeling. In part, this requires testing of predictive models against observation-constrained ice sheet histories, ideally for periods that were warmer than present [e.g., Vaughan and Arthern, 2007]. Given

the current paucity of knowledge regarding the configuration of WAIS prior to the last LGM, we must seek new constraints where we can. After all, if A-W and perhaps, other seaways, opened during recent interglacials, it must be concluded that WAIS lost more ice than it has yet lost in the Holocene. Although in itself our analysis of biodiversity analysis is insufficient to provide such a history, it does, perhaps, begin to provide such a

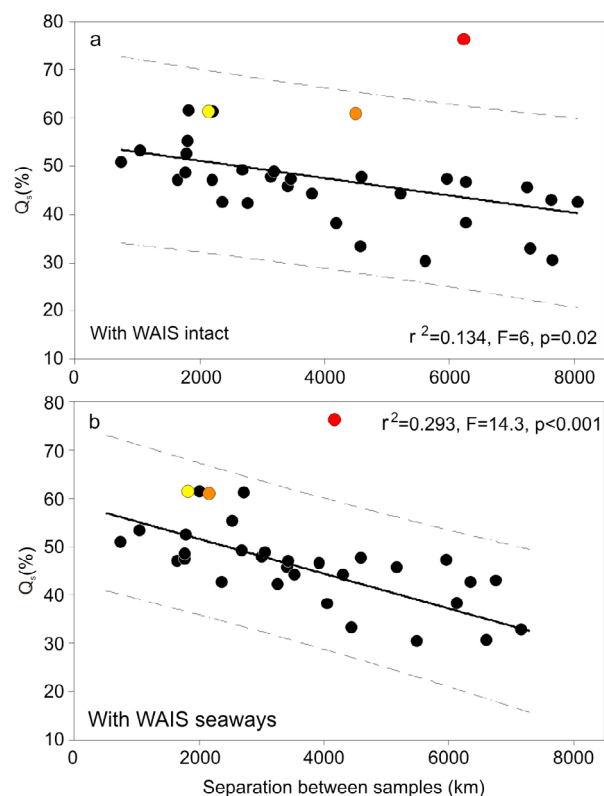


Figure 5. Sørensen's Similarity index (Q_s) of bryozoan species in pairs of sites that include at least one site in West Antarctica as a function of the sea distance between the centers of those sites (see Figure 3) calculated (a) with all WAIS seaways intact and (b) with seaways (B-W, A-W, A-R) open. Specific pairs are highlighted by colored fill: red, Ross and Weddell seas (R-W); orange, Amundsen and Weddell seas (A-W); yellow, Amundsen and Ross seas (A-R). Dashed lines are 95% confidence interval.

resource and shows the potential benefit of biological evidence.

[25] In future, we may be able to use population genetics of coastal marine species, or dating of the marine exposure of sub-glacial sediments along candidate seaways, to date with confidence the final closure of specific WAIS seaways. But either of these exercises would require a very substantial research and logistic commitment, and neither has yet to be secured. We hope that our analysis will establish a sufficiently strong hypothesis for opening of WAIS seaways that such work will indeed be possible in future.

Acknowledgments

[26] We thank colleagues at British Antarctic Survey; in particular, C-D Hillenbrand, HJ Griffiths, RD Larter, EW Wolff and L Sime for constructive advice. This study was funded by the Natural Environment Research Council and the EU FP7 program ice2sea (grant 226375, publication 021), and is part of the British Antarctic Survey program, Polar Science for Planet Earth.

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